MASTER

TITLE
SUPERNOVA HYDRODYNAMICS

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SNEORNOVA HYDRODYNAMICS
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ABSTRACT
The explosion of a star supernovae occurs at the end of its evolution when the nuclear fuel in its core is almost, or completely, consumed. The star may explode due to a small residual thermonuclear detonation, type I SN or it may collapse, type I and type II SN by neutrino neutron star remnant. The type I progenitor should be thought of as an old, accreting white dwarf, 1.4 M\(_\odot\), with a close companion star. A type II SN is thought to be a massive young star, 6-10 M\(_\odot\). The mechanism of explosion is still a challenge to our ability to model the most extreme conditions of matter and hydrodynamics that occur presently and excessively in the universe.

1. INTRODUCTION

A position in the sky associated with a distant galaxy brightens up for a period of a month with a luminosity comparable to the galaxy as a whole. The phenomenon, known as a supernova, is associated with the explosion of a star because the mass required to emit this luminosity at the inferred temperature is of the order of a stellar mass. The simplest explanation for the observed luminosity requires the diffusion of radiation from an internal energy source and the further assumption that the star has expanded to a dimension sufficient to give the necessary radiating area as well as to allow the diffusion of radiation from its interior. The time to maximum luminosity and the width of the peak luminosity are comparable to the inferred expansion rate and so the inferred expansion rate is of the order of 10\(\text{cm s}^{-1}\). This velocity is substantiated by the Doppler shifts of the lines observed in the early stages. This general description of the dynamical expansion of a SN is the reason for interpreting the phenomenon as a stellar explosion.

2. THE ORIGIN OF THE LIGHT

Let us illustrate this with the appropriate numbers. Luminosity at maximum of a type I supernova is \(10^{51}\) ergs, depending on \(M_e\) equal to 70 or 35 (Branch 1981). It rises to maximum light within roughly 10 days or \(8 \times 10^3\) s and has a color temperature of \(1.5 \times 10^4\) degrees with line blanking in the ultraviolet that prevents any (~1%) of the UV from escaping. Then the surface area of the matter that must be emitting no hydrogen in the optical, becomes

\[
A = \frac{b}{c/4 \pi v^2}
\]

where \(b\) is the bolometric correction for radiation with a cutoff above the blue band, \(\lambda > 3400\) Å, from a body at 15,000 K. The solid angle of a star of radius \(R = 10^{10}\) cm is \(4 \pi R^2 / c^2\), so that \(A = 10^{31}\) cm\(^2\) and the radius at maximum light is \(10^{18}\) cm. The mass required to emit the radiation depends upon the opacity which in turn is dependent upon the material and the relatively negligence of line blanking (Fukugita, R. 1981; Colgate and Panosh 1981; Karp et al 1974).

A relatively conservative value for the opacity corresponding to a typical heavy element at low density and this temperature is \(\kappa = 0.03\) cm\(^2\) g\(^{-1}\). Line blanking enhances this by a factor of times 3 or \(\kappa = 0.1\) cm\(^2\) g\(^{-1}\) as estimated by Karp et al (1977). If we believe that radiation must diffuse out within the time of the width of the maximum of the light curve \(\Delta t = 10^3\) s, then the optical thickness becomes

\[
t = c/\sqrt{\text{surface}} = 35
\]

and the mass becomes

\[
M_e = \frac{\Delta t}{c} = 10^{33} \text{ g} = \frac{b}{\kappa} M_\odot
\]

This is why a SN is interpreted as the explosion of an entire star.

Type II SN also have recently been observed in the UV (Panagia et al 1980) and the spectra show a combination of narrow and broad emission lines as well as a UV excess above the Planck value. This is interpreted as ejected matter colliding and forming a far extended envelope of pre-SN stellar wind, \(R > 10^{17}\) cm, (Fronay 1981). This collision then supplies the energy later emitted as optical and enhanced UV emission. But does this type I emit light without such a collision source?

SN 1A's show no hydrogen in the spectra and as previously noted no UV emission. Since the kinetic energy supplied by the expansion velocity is so much \(M_e \nu_e / 2 > 5 \times 10^{50}\) ergs, compared to
an optical emission of \( \approx 2 \times 10^{49} \) ergs, we might naively believe that the original heat of the explosion would be adequate following expansion. Let us generously estimate this heat as being both the kinetic energy as well as an initial gravitational binding energy of \( E = 5 \times 10^{51} \) ergs, i.e., ten times greater than the kinetic energy. The radius corresponding to the gravitational energy is \( R = R_k (H,G/M) = 10 \) cm. We have already assumed no subsequent collisions of the ejected matter (including stellar remnant formation) and so the expansion will be adiabatic and the internal energy will decrease at least as fast as \( 1/R \) for radiation dominated matter, \( \gamma = 4/3 \).

Therefore, adiabatic expansion will decrease the internal energy by the ratio \( R/R_{\text{opt}} = 10^{-1} \). This is such a large decrease that no reasonable assumption of initial energy content can account for the optical radiation. A late time energy source is required. It is now almost universally agreed (Colgate and McKee 1969; Axelrod 1980; Weaver, Axelrod, and Woosley 1980; Colgate, Petashkov, and Kriese 1980) that the late time energy must be derived from the radioactive decay of \( ^{56}Ni \), formed by nuclear synthesis in the exploding star. If we rearrange alpha particles by thermonuclear reactions of alpha particle nuclei, i.e., C, O, Si, carbon oxygen and silicon, then the minimum energy nucleus is \( ^{56}Ni \). This decays to \( ^{56}Fe \) (37 days) which accounts for the large abundance of iron in the universe. It also conveniently accounts for the peculiar optical decay curve of SN 1 when the transparency loss of radioactive gamma rays and positrons is included in the calculations of luminosity, Figs. 1 and 2.

There is still a disagreement as to whether the long-time optical decay of 56-day half-life is produced by positron loss (Arnett 1980; Colgate, Petashkov, and Kriese 1980) or infrared emission (Axelrod 1980) but this uncertainty may be resolved by the calibration of the peak luminosity and \( M_\gamma \). This is because the two models of an SN I type I explosion collapse to a neutron star (NS) or a thermonuclear explosion (TN) produce \( M_\gamma \) ejected or 1.5 \( M_\odot \) ejected, respectively, and the ejected mass in turn determines the density and hence late time infrared emission. The optical and UV emission by its time variation and intensity describe a star exploding with a velocity characteristic of the gravitational binding of the late stages of evolution.

3. THE INSTABILITY THAT STARTS EXPLOSION

The great success of stellar modeling using gravity, mass, radiation transport, and nuclear reactions leads one to the inevitable conclusion that the stellar explosion is the result of late nuclear evolution to some unstable end point.

There are now recognized three unstable end points of nuclear synthesis. These are, in order of decreasing mass of the parent star:

1. The electron positron pair instability (Pressley 1968) for stars heavier than \( \sim 75 \) \( M_\odot \). Here at a late stage in evolution with an oxygen or heavier core, the radiation pressure support is weakened by the specific heat of the rest mass of the weak relativistic pairs and collapse to a

Fig. 1. The calculated luminosity at early and intermediate times for \( M_\gamma = 0.25 \) solar masses and the corresponding deposition functions for \( \gamma = 1 \) at 20 days and 40 days. Gamma-ray deposition and the \( Ni + Co + Fe \) decay determine the solid curves. The dashed curve is the modification of the deposition function due to diffusion and expansion (Colgate and McKee 1969). The extrapolation of the deposition curves reaches \( 2 \times 10^{48} \) ergs at \( t = 0 \), and the difference between this and the dashed curve is due to heat energy converted to kinetic by expansion. The circles give NGC 5253 data (Kirshner and Oke 1975), and squares give NGC 4182 data (Baade and Zwicky 1938; Van Hise 1974).

Fig. 2. Same as Fig. 1 for times out to 700 days. Here the curves are primarily determined by the deposition of positrons from the Co-Fe decay. The dashed curve is a fit to the data with a slope corresponding to a 56-day half-life.
neutron star or black hole results. The number of such massive stars, according to the present stellar mass function (Miller and Scalo 1979) are too few to account for either type of SN and more particularly supernova type II's and neutron stars.

2. A more reasonable mass for SN II's is ~ 25 M☉ and then the original suggestion of Burbidge, Burbidge, Fowler, and Hoyle (1957) applies and collapse is initiated by the thermal decomposition of iron back to alpha's and neutrons. The extensive nuclear synthesis calculation of Arnett (1977); Weaver, Zimmerman, and Woosley (1978) confirm the evolution to the instability. A still more recent calculation of stellar nuclear synthetic structure is given in Fig. 3 from Weaver and Woosley (1980). This nuclear structure is exceeding complex and would be very different if convection were driven by rotation or magnetic fields. Following collapse, an explosion of the star results presumably by the energy from the creation of a neutron star. However, despite the desire by theorists to explain this explosion, a truly convincing description is still illusive.

3. Finally, a type I SN is most likely a thermonuclear instability, but with two possible outcomes. The thermonuclear instability is associated with the thermonuclear burning of a carbon-oxygen stellar core. This may be initiated off center in a mantle of helium that detonates. This then leads to the detonation of the high density core and therefore an off-center explosion (Nomoto, Marisi, and Sugimoto 1979; Nomoto 1980; and Weaver, Axelrod, and Woosley 1980). The helium mantle is most likely formed by accretion from a helium star companion onto a white dwarf. Alternately, the core may initiate carbon-oxygen burning at the center by pico-nuclear reactions. Then a detonation or deflagration may result and this may have two very different outcomes as indicated in the section on light curves. The deflagration or deflagration may result in the entire disruption of this star or following deflagration only the beta decay via electron capture of the heavy nuclei may be fast enough such that collapse results before explosion (Buchler, Mazurek, and Colgate 1979). In this case a collapse to a neutron star would result and an explosion would occur similar to the SN II explosion.

Fig. 3. Presupernova composition profile of a 25 M☉ Population I star as a function of the interior mass coordinate as given by WSN. The structure is shown at the point at which collapse velocities in the iron core have nearly reached 1000 km/s and are rapidly increasing. In the region interior to 1.61 M☉ where a 131-isotope quasi-equilibrium nuclear-burning network was used to treat quasi-static silicon burning and neutronization, the curve labeled 49Fe includes minor contributions from other A ≥ 22 iron peak nuclei; the curve labeled 56Fe includes those iron peak isotopes with A = 2Z + 1, while that labeled "Fe" includes all other isotopes with Z > 22 (e.g., 60Fe, 56Fe, and major contributions from highly neutronized iron peak species such as 44Ca, 54Mn, 60Ti, etc.). For additional details and a similar plot for a 15 M☉ star, see WSN.8
The mass ejected in the case of collapse would be
only \(-0.5\ M_\odot\) and perhaps \(0.25\ M_\odot\) of \(10^4\ M_\odot\). The
thermonuclear explosion on the other hand would
ject \(1.5\ M_\odot\), of which at least \(1\ M_\odot\) would be
\(10^4\ M_\odot\). Possibly the light curve from early SN I's
will tell the difference. Possibly a more accu-
rate budget of iron in the galaxy will tell the
difference. Also the current estimate of the
galactic rate of SN is 1 per 20 to 40 years
(Tammann 1981) and the error in the neutron star
production rate in the galaxy is also 1 per 20 to
40 years (Hills 1980). This then also allows
either possibility, namely, neutron stars may
result from SN II only or from both types of SN.

4. STATISTICS OF NEUTRON STARS AND SUPERNOVAE

Certainly many neutron stars as seen in the
Galaxy and a few, the Vela and the Crab, are
uniquely associated with SN events. Unfortu-
ately, all the historical SN do not uniquely have
neutron stars and their types cannot be uniquely
determined from the records (Clark and Stephenson
1977). Furthermore, all neutron stars
might not be expected to be visible because of
possible beaming of the supernovae
radiation.

To summarize, stellar instability at the end point
of evolution has two significantly divergent
possibilities: i.e., collapse to a neutron star or
a thermonuclear detonation. These alternatives
are not yet resolved. We will now discuss these
alternative mechanisms in greater detail.

5. THERMONUCLEAR EXPLOSION AND COLLAPSE

The off-center explosion depends upon the slow
accretion from a red giant envelope of a helium
companion star to a helium envelope building up on
a white dwarf star. This accreting layer of
helium burns at its base, building up A carbon-
oxxygen core. Depending upon the core mass, helium
accretion rate, and core density, the helium shell
may or may not detonate before ignition of carbon
burning at the center. The carbon burning may
also be initiated at high density by pico-nuclear
reactions which depend upon the electron
degeneracy. In either case the central density of
the ignition will be roughly \(10^{10}\ \text{g cm}^{-3}\). At this
high density, the electron degeneracy pressure
is significantly greater, times \(10\), than the incre-
mental pressure arising from complete thermonu-
clear burning of a carbon-oxygen core of \(10^4\ M_\odot\).
Hence, the pressure wave arising from the thermo-
nuclear energy is only a strong sound wave and a
very weak shock. Hence a detonation wave is not
dependent on only in the case of the helium
ingestion is a driven shock likely to be strong
enough to initiate the near simultaneous SN igni-
tion of the entire core. The subsequent history
of the core is then determined by the competition
between electron capture which rapidly decreases
the pressure by removing electrons from the top of
the Fermi sea (7 to 8 MeV) and disassembly that
occurs at a fraction, \((-1/3)\) of sound speed.
\(10^7\) cm and sound speed
\(2 \times 10^8\ \text{cm s}^{-1}\), or a time of \(0.05\ \text{s}\). Since the
core must bounce, the total time is \(-1/10\ \text{s}\). In
this time the electron capture is just about rapid
enough to remove 10% of the pressure and collapse
to a neutron star would ensue. Collapse or TN
explosion therefore depends sensitively upon the
electron capture rates as well as the hydrodynam-
ics of the helium detonation shock core compres-
sion. The capture rates depend sensitively upon
the Fermi level, hence, density and hence radius,
roughly \(\sim (\text{radius})^3\) yet the core is close to
unstable collapse due to gravity and relativistic
degeneracy. Hence, the issue of collapse or TN
explosion requires very detailed knowledge of the
equation of state, core structure, beta decay
rates, and finally the hydrodynamics of an off-
center explosion.

have significantly revised the electron capture
rates due to "beta decay blocking." This results
in an increase in the capture rate at the pre-
collapse density, \(\sim 10^{11}\ \text{g cm}^{-3}\) and a large
decrease in the rates at early collapse, a few \(10^7\ \text{g cm}^{-3}\).

Finally, if carbon-oxygen burning initiates at
the center by the star, the situation leads to a defla-
ration rather than detonation because of the
weak, \(\sim 10^5\), overpressure from TN burn. Defla-
gation consumes a core at the rate of turbulent
plume mixing which will take considerably longer
than a sound wave traversal time by roughly the
time of the solid angle of a plume to that of the
full sphere, or by roughly a factor of \(4\). Hence,
the deflagration time is closer to the time of
more time for electron capture than shock wave
initiation. This leaves the issue of collapse or
TN detonation for type I SN uncertain.

6. TYPE II SUPERNOVA

Type II SN are more massive stars that evolve
a higher adiabat, i.e., more temperature for a
given density, and hence burn carbon and oxygen
degenerately and stably to a core Fe as shown
in Fig. 3 (Weaver and Woosley 1980). The col-
apse of the core when all available fuel is
burned is inevitable. The results may or a neu-
tron star or a black hole. The existence of
neutron stars would dictate that the usual result
is a neutron star, but just how is still slight-ly
uncertain.

Bethe, Applegate, and Applegate (1980) have
recently completed the most exhaustive analysis of
the problem of forming a supernova explosion from
the formation of a neutron star. This work takes
into account the latest understanding of the
equation of state, neutron trapping and diffusion,
hydrodynamics of collapse and core bounce shock
formation. We give only a brief description of
this phenomenon, but with some emphasis on the
points of uncertainty.

7. SUPERNOVA TYPE II COLLAPSE

The iron core of a reasonably massive star, \(6\)
to \(10\ M_\odot\), is partially degenerate at the end of TN
burning with a low entropy \(S/k < 1\). As collapse
proceeds, almost all the leptons are trapped
because 1. blocking reduces electron capture and
easily collapse, and 2. neutral current neutrino
scattering traps the neutrinos. The leptonic frac-
tion \(Y_L\) decreases from that of iron \(S = 0.48\) to
\[ V_p = 0.35 \] and hence the pressure is significantly reduced. (Nuclei do not contribute significantly to the pressure.) Hence, a fraction of the core collapses homologously (\( \sim 0.75 \, M_\odot \)) the mass corresponding to the new Chandrasekhar limit associated with the reduced \( V_p \). This new homologous core bounces at just above nuclear density (nuclear matter is stiff) initiating a shock wave at the homologous core boundary.

8. THE BOUNCE SHOCK

It is presumed that this shock causes the SN explosion. This core bounce shock climbs out through the imploding matter heating it to a high temperature \( kT \approx 10 \text{ MeV} \) in high entropy \( S/k \approx 7 \) to 10 which dissociates the nuclei back to free nucleons. The shock is weakened by dissociation and lepton degrees of freedom. It is strengthened by the density gradient. Numerical calculations indicate a weakening due to neutrino emission. Analysis would say that neutrino diffusion behind the shock should strengthen or aid the shock because diffusion allows thermal conduction to transport heat from the inner higher density, higher temperature regions to the outer, lower density regions behind the shock, i.e., forming an isothermal shock. On the other hand, neutrino leakage (at low energy, small cross section) should definitely weaken the shock. Further out where neutrinos will be trapped, thermonuclear burning will aid the shock as well as the re-combination (thermonuclear burning) of the previously shocked decomposed nuclear matter. These gains and losses are so complicated that an unequivocal prediction is not possible but it is certainly plausible that this is the mechanism of SN created from collapse.

There are several further complexities like degenerate lepton-driven core convection and violent overturn, post ejection, rarefaction collapse, and neutrino luminosity stress that have yet to be fully resolved. Nevertheless, the great advance is the detailed analytical reproduction of much of the numerical modeling. This has strengthened the physics basis of the understanding of SN.

9. EJECT VELOCITY DISTRIBUTION

The optical evidence and its interpretation is the reason for believing that supernova ejection is roughly solar mass at high velocity. A shock wave inevitably precedes such an explosion, and depending upon the structure of the mantle of the presupernova star, i.e., a compact star for type I SN, this shock can become relativistic before reaching the surface of the star (Colgate and White 1966). The extended envelope models of SN II, as already pointed out, give good agreement with observation and particularly UV observations, and in these models no high velocity ejecta is formed. Hence only in the case of SN I's do we foresee a possibility of relativistic ejecta. The mass fraction that becomes relativistic can be estimated from the solution of shock waves in density gradients and these estimates are confirmed by numerical studies (Colgate and White 1966). Recently this phenomenon of the shock wave speeding up in the envelope has been confirmed by calculations by Weaver, Axelrod, and Wooley (1980) for compact models of SN I. Fig 4. The mass fraction that becomes relativistic after the explosion of the post shock energy density is then roughly \( 10^{-5} \) to \( 3 \times 10^{-8} \) and so the total energy in relativistic matter becomes \( 10^{50} \text{ ergs} = 10^{49} \text{ ergs} \). This is adequate to power cosmic rays.

![Type I supernova models final velocity profiles](image)

(From Weaver, S. A., Axelrod, T. B., and Wooley, S. E., 1980, in proceedings of the Texas Workshop on Type I Supernova, ed. J. C. Wheeler, Univ. of Texas Press, Austin, Texas.)

Fig. 4. Final velocity profiles for Type I supernova models as a function of interior mass fraction. As in Fig. 1, major abundance discontinuities are indicated by bars.
in our galaxy provided the relativistic matter can escape from the region of the SN without degradation and with the appropriate energy distribution. The escape is a question of the effectiveness of Alfvén wave trapping (Kulsrud 1979) and the spectrum is determined by relativistic shock hydrodynamics (Colgate and Petschek 1978, Fig. 5). A summary of these questions with references is given in Colgate (1981).

10. REMNANT FORMATION

Remnant formation starts with the first interaction of the SN ejecta with the interstellar medium. The first indication of this may be the detection of the SN II 1979 c in radio emission, (Weiler et al 1980). Pacini and Savalii (1980) have interpreted this as pulsar emission, but the early time of detection (less than one year) would result in a high enough density of the SN ejecta such as to prevent the observation of an embedded source. There are not yet models that would predict this very early remnant emission by nonthermal electrons.

Later stages of remnant formation are concerned with the development of a collisionless shock in the ISM. This structure of such a shock is still problematic (McKee 1974) yet extensive modeling of the origin of cosmic rays depends upon such a collisionless shock (Bell 1978a,b; Blanford and Ostriker 1978, 1980; Axford, Lear, and Skadron 1977).

11. SUMMARY

The whole of the supernova phenomenon is rich in physics as well as astrophysics and the observations and interpretation test our ability to model the most extreme observable phenomenon of the universe.

12. ACKNOWLEDGEMENT

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13. REFERENCES